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Engine Type Independent SCR System

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***Abstract* – In this paper is described a part of the system for the reduction of nitrogen oxides (NOx) in the exhaust system. The system is designed for diesel engines and the control electronics must be independent of the engine type. The principle of mass flow measurement of exhaust gases is also described. The results of the prototype system test preformed on the test bench are described. The paper deals also with the urea injecting.**

Keywords - SCR; NOx reduction; mass flow measurement; exhaust system

I. INTRODUCTION

At present the emission limit requirements are more and more restrictive. One of the possible ways how to decrease the amount of nitrogen oxides (NOx) emissions is the use the selective catalytic reduction (SCR). This system uses a special catalyst convertor in the exhaust system and it is able to reduce up to 99% of NOx.

The SCR systems are used mostly with new big diesel engines (in trucks, trains, etc.) and the control system is connected to the main control unit of vehicle. It means there is no universal SCR system. The goal of this project is to develop an independent exhaust system including the SCR and diesel particulate filter (DPF) [3] [4]. This paper deals with the SCR part.

II. PRINCIPLE OF OPERATION

During its runtime the combustion engine produces harmful emissions of NO and NO_2. These gases are highly toxic for a human. This is the reason why the reduction is needed. The selective catalytic reduction is based on injecting of an aqueous urea solution to the catalytic converter. In the catalyst converter the NOx react with NH_3 and get out as nitrogen (N_2) and water steam (H_2O).

The chemical formulas mentioned below describe the chemical reactions in the exhaust system [1]. The aqueous urea solution (commercial trademark ”AdBlue”) contains 32.5% of urea ($(NH_2)_2CO$) and water (H_2O). After injecting of urea into the exhaust the solution is evaporated and the urea will be thermally decomposed.

$$(NH_2)_2CO \cdot 7H_2O \rightarrow (NH_2)_2CO + H_2O \quad (1)$$

$$(NH_2)_2CO \rightarrow NH_3 + HNCO \quad (2)$$

Ammonia (NH_3) and isocyanic acid (HNCO) are absorbed on the surface of catalytic material, where the NH_3 reacts with the NOx and NHCO hydrolyzes with the water.

$$HNCO + H_2O \rightarrow NH_3 + CO_2 \quad (3)$$

The following reactions show the process of the selective catalytic reduction. There are 3 types of reactions – normal SCR (4), fast SCR (5) and slow SCR (6).

$$4NH_3 + 4NO + O_2 \rightarrow 4N_2 + 6H_2O \quad (4)$$

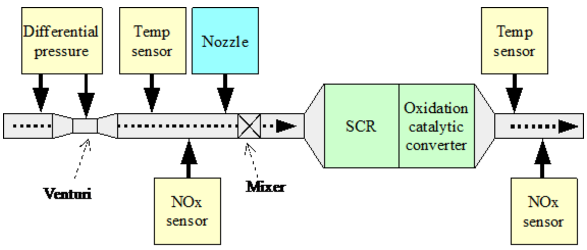
$$4NH_3 + 2NO + 2NO_2 \rightarrow 4N_2 + 6H_2O \quad (5)$$

$$8NH_3 + 6NO_2 \rightarrow 7N_2 + 12H_2O \quad (6)$$

III. THE EXHAUSHT SYSTEM

The block diagram of the exhaust system is shown in Figure 1. The base part of the exhaust system is the catalytic converter. It has two sections – SCR and oxidation catalyst. In the picture you can also see a position of the sensors and the urea injection point.

Figure 1. Block diagram of exhaust system



For the measuring of NOx concentration we use NOx sensors from Bosh manufacturer - EGS-NX. These sensors have their own control unit (SCU) which processes the signal from the probe and provides calculated values via CAN bus. The sensor can measure the concentration of O_2 together with NOx (the sensor is not able to recognize NO from NO_2). The sensor measurement range is 0 – 1650 ppm of NOx. The SCU provides also information about the status of the sensor, gives information about errors, etc. As the probe must be heated, the SCU ensures also a warm-up process.

The thermocouples are used for the temperature measuring. The gas temperature can reach up to 600°C. We chose the thermocouple type K, because it is capable to measure in this range and its output characteristic is sufficiently linear. The information about the temperature of exhaust gases is important for controlling of the whole system.

The nozzle is used for the urea injection. The main requirement is to dose the urea accurately. This device is in principle an electromagnetic valve. The nozzle produces a very fine aerosol. It ensures quick vaporizing and after that thermal cracking of the urea. Constant work pressure in the pipe system is necessary for correct function. The work pressure is over 5 bars. This pressure is ensured by a diaphragm pump [2]. A mixer is located behind the nozzle. It is used for a mixing of exhaust gases with the urea aerosol, uniform distribution of gases is necessary for good performance of SCR.

The principle of the SCR catalytic converter function was discussed in paragraph II. The second section of the converter is used for oxidation. Using of this type of converter is important because during the fuel combustion, not only nitrogen oxides arise, but also carbon monoxide (CO) and hydrocarbons (HC). The oxidation process ensures conversion of these harmful substances to nontoxic substances. The main reactions are principally described below (7-8).

$$2CO + O_2 \rightarrow 2CO_2 \qquad (7)$$

$$HC + O2 \rightarrow CO_2 + H_2O \qquad (8)$$

The surface of the SCR catalytic layer can absorb the ammonia. However, if we inject excessive amount of ammonia, the SCR converter will be overfilled. It means that more ammonia cannot be stored and it flows through the catalyst. The ammonia is also toxic and it should not be released into atmosphere. This is the reason, why the oxidation catalytic converter is positioned behind the SCR. Ammonia can also oxidize and there are three principally possible reactions which depend on the working conditions. The NH_3 oxidizes to nitric oxide and water steam, nitrogen dioxide and water steam or to nitrogen and water steam (9-11) [5] [6].

$$4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O \qquad (9)$$

$$4NH_3 + 4O_2 \rightarrow 2N_2O + 6H_2O \qquad (10)$$

$$4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O \qquad (11)$$

For low NOx emissions, it is important to inject accurate amount of urea. Excessive amount of urea would result in nitrogen oxides created by oxidizing of ammonia. On the other hand, insufficient amount of urea in the SCR converter would result in lower reduction efficiency and production of some nitrogen oxides. This task is the biggest challenge for the control system.

At present the system is just a prototype so the whole control system is divided into several parts. This distribution allows making easier changes. All subsystems communicate via the CAN bus. The main part is the "pump bus unit" (PBU). It drives the pump and controls the nozzle. The urea pressure sensor and the urea temperature sensor are connected the PBU. The second unit is used for the temperature measuring and the differential pressure measuring. The NOx sensors also communicate via CAN bus as it is stated above. A problem arose in the communication the sensors (Bosch samples) transmitted the same ID fields and it was necessary to separate the CAN buses and to use the bus translator which changes the CAN IDs.

IV. FIRST TEST

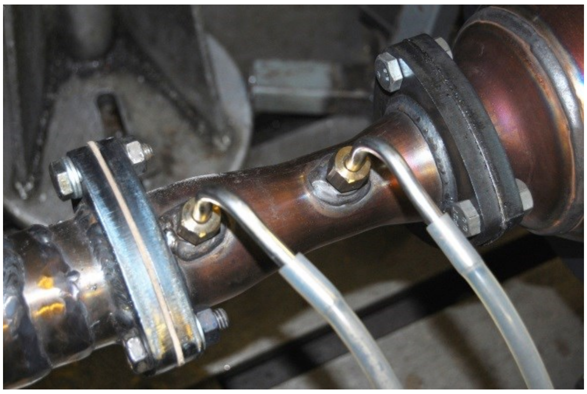
For the obtaining of the first real data, we prepared a test on the engine test bench. The exhaust system was connected to the IVECO 6-cylinders engine with a total volume of 6000ccm. The exhaust was connected to a gas analyzer. The engine was loaded by an electromagnetic brake. The engine test bench is depicted in the Figure 2. During the test we could observe the data about inlet air amount, input fuel amount, RMP, torque, etc. From the control stand we could control the engine accelerator pedal and the RPM of the engine breaks. These variables are closely dependent on torque.

Figure 2. The engine test banch with the SCR system

It is necessary to know the amount of NOx produced by the engine so that the correct urea amount for the injection into the exhaust system can be computed. The NOx sensors provide the information about NOx concentration, but no about its amount. Therefore it is necessary to measure a mass flow of exhaust gases.

The exhaust gases flow from the engine trough the exhaust pipeline into the catalytic converter. The pipeline is narrowed in one point (see Figure 3.). It is used for velocity measuring of exhaust gases. We use the Venturi effect, when the flowing fluid or gas causes the pressure drop between the pressure before and after the narrow part. This pressure difference corresponds to the velocity of the exhaust gases.

Figure 3. Narrowed exhaust pipeline for velocity measuring

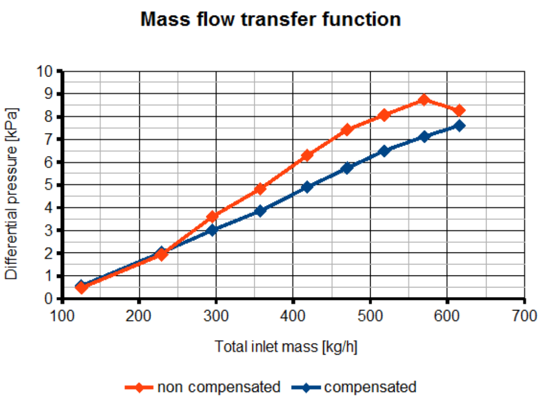


Because this device is able to measure only velocity, it is necessary to recalculate this value to the mass flow. We obtained a transfer function of the "Venturi tube" experimentally (it was not shaped exactly like the original Venturi tube). We measured the differential pressure in the Venturi tube, the inlet air mass flow into the engine, the mass flow of the fuel, and the temperature in the exhaust. These values have been measured in various running conditions and recorded. The mass flow in the exhaust is dependent on the differential pressure and also on the gas temperature. The temperature influence was respected by the formula (12), where P_{diff} is the measured pressure difference and $P_{compensated}$ serves for calculations of the mass flow.

$$P_{comensated} = \frac{2 * P_{diff} * 293}{T + 273} \tag{12}$$

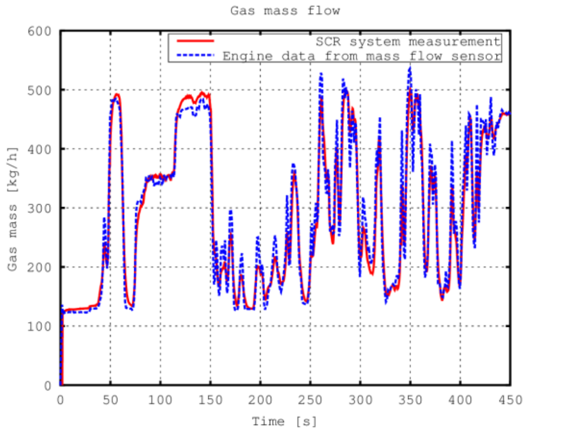
In the graph (Figure 4.) you can see the transfer function of the Venturi tube without and with the temperature compensation. On the X axis is the sum of the inlet air mass flow and the inlet fuel flow.

Figure 4. The transfer funcion for venturi tube



The correctness of calculations were verified by a transient test. The transient test is designed for simulating of real traffic conditions, and it is also used during the certification processes of various vehicles. The result can be seen in the Figure 5.

Figure 5. The comparison of mass flow measurement methods



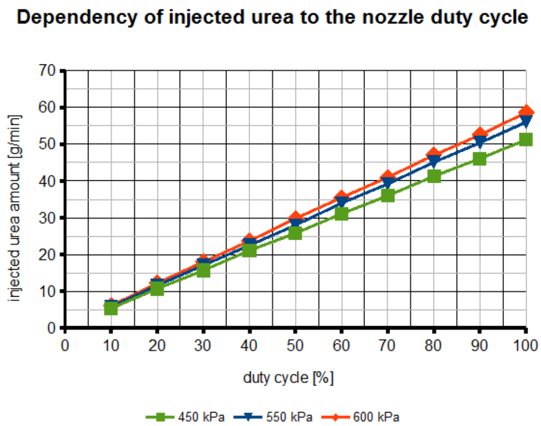
The transient test has shown that the Venturi mass flow measurement method is usable and that the control system can compute the NOx amount by simple multiplication of the NOx concentration and the exhaust gases mass flow.

V. UREA DOSING

The next important task was to test the behavior of the nozzle. As it is explained above, the nozzle works as an electromagnetic valve and it has only two positions – fully open or closed. It means that the control of urea dosing is possible only by the changing of the ratio between open time and close time. Because very quick changing of the nozzle state can damage the valve, we specified the minimal close or open time as 200 ms. This mode of control resembles the pulse-width modulation (PWM); however we did not use constant frequency. The minimum pulse width (200 ms) would sometimes lead to long period which it is unsuitable for uniform mixing of the urea and exhaust gases.

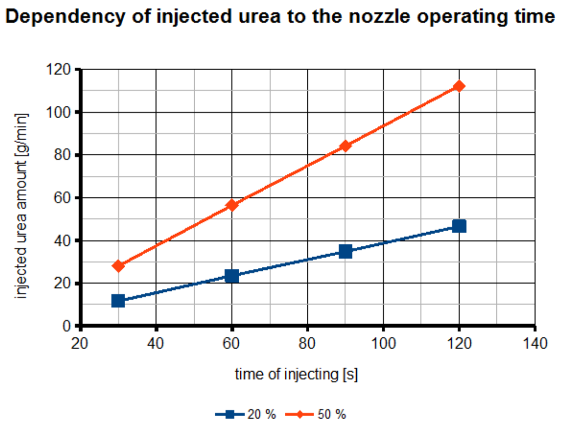
For example – in the case a 5% duty cycle the open time will be 200 ms (its minimal value) and the close time will be 3800 ms. It means the period will be 4 seconds long. However, in the case of a 40% duty cycle the period will be only 0,5 s (200 ms open, 300 ms close) and the injecting will be more uniform. This is the reason why we used a non-constant period.

Figure 6. The urea amount dependency on the duty cycle



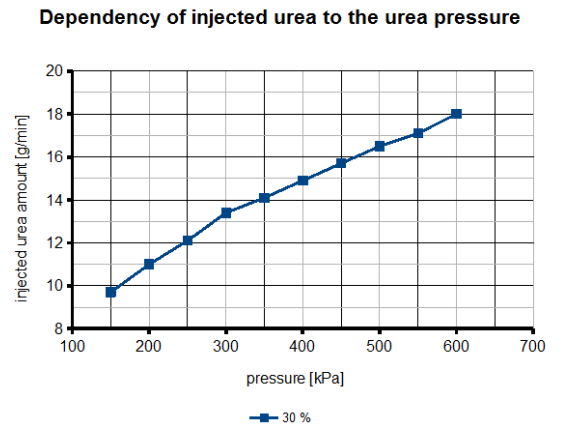
The behavior of the dosing system was verified by injecting the urea into a container for 30 seconds with various duty cycles. This test as repeated for 3 different pressures in the urea pipe system. The result is shown in the graph (Figure 6.). The dependency is linear, which simplifies the implementation of the control algorithm. Another figure (Figure 7.) shows the linear dependency of the injected amount on time for different duty cycles.

Figure 7. The urea amount dependency on time of injecting



As is seen in the graph (Figure 6.), the injected amount of urea is also dependent on the pressure. The dependency of injected urea on its pressure with a 30% duty cycle after 30 s is shown in the Figure 8.

Figure 8. The urea amount dependency on injecitng time



Measuring of the injecting system behavior was necessary for developing of the control algorithm. The tests provided a lot of useful data which were used in the injecting control.

VI. CONCLUSION

The prototype SCR system was developed and the first test was performed on the engine test bench. The behavior of the dosing system was mapped in various working conditions. For the measuring of input and output NOx concentration we used the Bosch EGS-NX sensors. We used the Venturi principle for measuring of the velocity of exhaust gases. This method was compared with the data from the engine mass flow meter and both corresponded. With the temperature measuring we are able to compute a mass flow of NOx in the exhaust. This value is used for the urea injecting control. Future work will be mainly focused on the optimization of control algorithms and on increased efficiency. Additionally we plan to improve mechanical parts and eliminate mechanical problems.

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